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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THE OSCILLATING FORCES AND MOMENTS ON A TWO-DIMENSIONAL WING EQUIPPED WITH AN OSCILLATING CIRCULAR-ARC SPOILER

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EXPERIMENTAL INVESTIGATION OF THE OSCILLATING FORCES AND MOMENTS ON A TWO-DIMENSIONAL WING EQUIPPED WITH AN OSCILLATING CIRCULAR-ARC SPOILER

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SUMMARY

Results are presented of an experimental investigation in the Langley 2- by 4-foot flutter research tunnel on the oscillating forces and moments on a two-dimensional wing equipped with an oscillating circular-arc spoiler. The forces and moments and their phase angles with respect to spoiler motion were determined from measurements of the instantaneous pressure distribution and the nature of the flow over the wing was studied with schlieren photographs. Data are presented for Reynolds numbers from 1.3×10^6 to 6.3×10^6, Mach numbers from 0.20 to 0.82, and reduced frequencies from 0 to 0.92. The results of this study indicate that the force and moment coefficients and their phase angles are affected in a complex manner by Reynolds number, Mach number, and reduced frequency.

INTRODUCTION

Aeroelastic vibratory instabilities on some present-day high-performance aircraft equipped with spoiler controls have indicated a need for knowledge of the oscillatory aerodynamic coefficients resulting from a spoiler projection or spoiler oscillation. Various wing-model investigations have shown the possible importance of spoilers on wing flutter. For example, reference 1 has shown that a fixed or rigid spoiler may affect the flutter speed of a wing while references 2 and 3 have shown that the spoiler dynamic characteristics relative to the wing may strongly affect the flutter speed. Aerodynamic studies on wings equipped with spoilers have been concerned with the steady aerodynamic loads associated with fixed spoilers and there has been little or no attention directed to the unsteady aerodynamics of oscillating spoilers. The aerodynamics for the case of either the fixed or oscillating spoiler involves the dynamics of separated flows and, in general, will be nonlinear and, to a certain extent, random as well.

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In view of the lack of information on the air forces associated with oscillating spoilers, and in view of the difficulties present in the analytical development of these forces, an experimental program was undertaken to attempt to gain some knowledge of the air forces on a rigid wing due to an oscillating spoiler. Of the many varied types of spoilers and spoiler configurations, the particular case that was investigated is that of a circular-arc full-span spoiler oscillating through a constant amplitude on a two-dimensional fixed wing. The aerodynamic normal-force and pitching-moment coefficients acting on the airfoil, due to spoiler oscillation, and their respective phase angles have been experimentally determined over a range of Mach number, Reynolds number, and reduced frequency.

These coefficients admittedly do not constitute a complete set of coefficients for a flutter analysis. However, the information presented may provide data of significance for the understanding of the spoiler influence on wing flutter in certain cases. In addition, the results should be of interest in connection with aspects of the problem of non-steady separated flows.

The tests were conducted on a two-dimensional 2-foot-chord wing with an NACA 65-010 airfoil section in the Langley 2- by 4-foot flutter research tunnel. A full-span spoiler was located at the 0.7-chord position. The investigation covered a range of Mach number from 0.20 to 0.82, a Reynolds number range from 1.3×10^6 to 6.3×10^6, and a reduced-frequency range from 0 to 0.92. The wing aerodynamic oscillating normal forces and pitching moments due to the spoiler extension and their phase angles with respect to the spoiler position were determined from measurements of the instantaneous pressure distribution. The pressures were measured by means of 20 NACA miniature electrical pressure gages located in a chordwise band. The nature of the flow over the wing was studied by means of schlieren photographs.

SYMBOLS

c chord of wing, ft

f frequency of oscillation, cps

C_m instantaneous value of oscillating aerodynamic pitching-moment coefficient about quarter chord

$|C_m|$ absolute magnitude of fundamental component of oscillating aerodynamic pitching-moment coefficient about quarter chord, $|M_\alpha|/qSc$ where $|M_\alpha|$ is magnitude of fundamental component of aerodynamic pitching-moment about quarter chord

[redacted]

C_N instantaneous value of oscillating aerodynamic normal-force coefficient

$|C_N|$ absolute magnitude of fundamental component of oscillating normal-force coefficient, $|N|/qS$ where $|N|$ is magnitude of fundamental component of normal force

k reduced-frequency parameter, $\omega c/2v$

M Mach number

q dynamic pressure, lb/sq ft

R Reynolds number

S area of wing, sq ft

v air velocity, fps

x distance along chord from leading edge, ft

δ/δ_{max} spoiler projection ratio

ϕ_m phase angle between fundamental component of moment and spoiler position

ϕ_N phase angle between fundamental component of normal force and spoiler position

ω circular frequency of oscillation of spoiler, $2\pi f$, radians/sec

APPARATUS

Model

The wing tested spanned the test section and had a 2-foot chord with an NACA 65-010 airfoil section. It was constructed with an H-type main spar attached rigidly to the tunnel walls to prevent motion of the airfoil. A thick skin of aluminum alloy was fabricated to give the airfoil shape and was attached to the spar in spanwise sections to allow access to the pressure gages and the spoiler mechanism. The spoiler spanned the model at the 0.7-chord location and was hinged at 0.6 chord. The geometry of the spoiler installation is shown in figure 1. The spoiler was oscillated in approximately sinusoidal motion by an induction motor-eccentric arrangement shown schematically in figure 2. The motor drove a flywheel which had an eccentric plate to which the connecting rod was attached, and [redacted]ed a bell crank which was fixed to the spoiler drive shaft. The spoiler was operated from 0 to 35 cycles per second and its maximum amplitude was 0.50 inch (2.1 percent of the chord) from the wing surface normal to the plane of the chord, and it traveled from the wing surface to its maximum amplitude back to the wing surface in one cycle of oscillation.

Tunnel

The tests were conducted in the Langley 2- by 4-foot flutter research tunnel which is of the closed-throat single-return type. The testing medium employed was air at pressures varying from 1/4 atmosphere to 1 atmosphere allowing a Reynolds number range from 1.3×10^6 to 6.3×10^6.

Instrumentation

The position and frequency of the spoiler motion were obtained from a photoelectric position indicator whose output was recorded on a multiple-channel recording oscillograph. The instantaneous pressure distributions were obtained by the use of miniature electrical pressure gages of the type reported in reference 4. Twenty gages were installed along a chordwise line in the center span section of the model as shown in figure 1. Their resulting individual electrical outputs were recorded simultaneously with the spoiler position.

The schlieren apparatus employed was of the standard type except in the control of the light source which was capable of operating continuously or at any desired flashing frequency. A reflecting knife edge was used to direct half the light into the camera and the other half was reflected to a viewing screen, thereby allowing an observation of the flow to be made before actually photographing the condition. The flashing of the light source was synchronized with the spoiler deflection thereby stroboscopically stopping the motion. This synchronization was maintained regardless of the spoiler frequency through the electrical connection of the light-source power supply with the output of the spoiler position indicator. A phase shifting circuit was built into the system for the purpose of delaying the signal from the position indicator to the light-source power supply so that the motion of the spoiler could be stopped stroboscopically at any desired point on the spoiler cycle. The schlieren photographs were obtained using one flash per photograph for the various spoiler positions.

DATA REDUCTION

Three typical consecutive cycles of each trace of the pressure gages on the oscillograph records were selected for analysis. Ten equally spaced (in time) intervals were read for each cycle. Where the traces representing the pressures had random fluctuations, faired curves through the irregular traces were read. The resulting pressure coefficients at each interval of time were integrated to yield "instantaneous" normal-force and pitching-moment coefficients by weighing the output of each pressure gage according to its location. The instantaneous coefficients at corresponding points on the three cycles were averaged and the average values were used in a 10-point Fourier analysis to obtain the magnitude and phase of the fundamental component.

The absolute values of the force and moment vectors as determined from the Fourier analysis were cross-plotted against Reynolds number R and reduced frequency k for constant Mach numbers. From these curves the effects of R, M, and k were obtained on the forces and moments. From similar crossplots the effects of R, M, and k on the phase angles of the force and moment coefficients were studied.

RESULTS AND DISCUSSION

The oscillating forces and moments and their respective phase angles on a two-dimensional wing equipped with a circular-arc oscillating spoiler are presented graphically in figures 3 to 9 and show some effects of Mach number M, Reynolds number R, and reduced frequency k on these forces, moments, and phase angles. However, before discussing these effects, some mention will be made of the sign convention used and the fairing and interpolations which were made in obtaining the results.

The above-mentioned coefficients and phase angles are shown diagrammatically in figure 3. In the upper right-hand corner is a sketch of the airfoil with the sign convention defined. The normal-force coefficient is considered positive when the normal force acts downward and the moment coefficient is considered positive when there is a pitching-up moment. Spoiler projection upward from the airfoil surface is considered positive.

The fixed wing was at essentially zero angle of attack and the spoiler oscillated upward from 0 to 0.021c. The spoiler motion was essentially sinusoidal as shown in figure 3(a). Due to the nonlinear behavior of the boundary-layer separation, the electrical outputs representing pressure changes over the wing were not sinusoidal, nor were the instantaneous normal-force and pitching-moment coefficients. As previously mentioned, three consecutive cycles were divided into thirty equal intervals and the coefficients were averaged for each time interval. Typical faired curves through these values are shown indicated as "instantaneous values" in figures 3(b) and 3(c). In order to simplify the presentation of data, the magnitude and phase angle of the fundamental component were extracted from the instantaneous values by Fourier analysis. The resulting magnitudes and phase angles are indicated in figures 3(b) and 3(c) by the sinusoidal curves marked "fundamental component."

Four dependent variables, $|C_N|$, ϕ_N, $|C_m|$, and ϕ_m, were obtained as functions of three independent variables, namely R, M, and k. In order to obtain the separate effects of Reynolds number, tests were conducted at three test-medium densities. In order to vary Mach number and reduced frequency independently, the frequency of oscillation was varied for each test velocity. The magnitudes and phase angles of the fundamental components of normal force and pitching moment have been extracted from the data obtained in this manner and are shown in figures 4 to 7. Each dependent variable is shown separately as a function of reduced frequency for constant values of Mach number and Reynolds number.

It is of interest to see how the three independent variables R, M, and k affect the forces, moments, and phase angles. For each variable and set of conditions shown in figures 4 to 7, faired curves were drawn through the data points. The effects of R, M, and k were obtained from cross-plotting values from these faired curves. In general it was found that Reynolds number had no consistent effect on $|C_N|$, ϕ_N, $|C_m|$, or ϕ_m, as it sometimes caused an increase for certain ranges of M and k, and for other ranges, caused a decrease. In most cases, the variations with Reynolds number were relatively small.

The effects of Mach number on $|C_N|$, ϕ_N, $|C_m|$, and ϕ_m are indicated in figure 8 for a Reynolds number of 2×10^6. It is noted that $|C_N|$ increases with Mach number and $-\phi_N$ decreases; that is, the angle by which the normal force lags the spoiler position becomes less. The value of $|C_m|$ remains more or less constant whereas $-\phi_m$ decreases (moment lags the position by a lesser amount). Generally, these effects were obtained throughout the range of test Reynolds numbers.

The effects of reduced frequency on the coefficients and phase angles are indicated in figure 9 for $R = 2 \times 10^6$. It is shown that $|C_N|$ decreases with k and the angle by which the force lags the spoiler displacement $-\phi_N$ increases. The value of $|C_m|$ increases with k whereas $-\phi_m$ increases or decreases depending upon the Mach number. There appears to be a 180° phase shift at $k = 0$ between $M = 0.4$ and $M = 0.5$ at this Reynolds number. The above-mentioned effects generally occurred throughout the range of Reynolds numbers tested.

It may be of interest to examine some sample records of the pressure variations and spoiler displacements as shown in figures 10 and 11. Figure 10 is a reproduction of a typical oscillograph record obtained while the spoiler was oscillating very slowly, simulating a steady-state condition. Indicated in the figure are the spoiler position, pressure gage location, and direction of increasing or decreasing pressure. The flow behind the spoiler near the trailing edge (traces 0.90 and 0.95) is apparently quite turbulent when the spoiler is extended. Flow directly behind the spoiler (gages 0.72 and 0.80) is also somewhat disturbed. The magnitude of the indicated high-frequency pressure fluctuation could not be determined accurately as its frequency was beyond the range of flat response of the galvanometer. For the oscillating condition (fig. 11) the high-frequency pressure fluctuations are quite similar to those shown in the steady-state condition.

An examination of photographs of the flow as the spoiler is oscillated may afford some insight as to what is happening to the flow over the airfoil (fig. 12). The photographs are arranged counterclockwise to show one cycle of spoiler oscillation. Thus, opposite photographs, such as parts (b) and (j) of figure 12, show the same spoiler projection noting that in figure 12(b) the spoiler motion is outward and in figure 12(j) the motion is inward. Note that the boundary-layer thickness at zero spoiler projection is about one-half the maximum spoiler projection. It is interesting to note that the portions of the curves in figure 11 which appear flattened occur during the time the spoiler projection is less than the initial boundary-layer thickness.

The time lag for the flow to follow the spoiler motion is indicated by a comparison of opposite photographs, for example, parts (d) and (h) of figure 12. In figure 12(d), where the spoiler is moving out, the flow tends to come back toward the airfoil; whereas, in figure 12(h) (spoiler moving in), the flow tends to continue away from the airfoil.

CONCLUSIONS

From the results of an experimental investigation of the forces and moments on a two-dimensional wing equipped with an oscillating circular-arc spoiler, the following conclusions may be drawn:

1. The effects of Reynolds number on the normal-force and moment coefficients and their phase angles were relatively small and somewhat erratic.

2. An increase in Mach number consistently increased the normal-force coefficient and decreased the phase lag of the normal force. Mach number had no consistent eff[redacted] coefficient; however, the phase lag of the moment decr[redacted]sing Mach number.

3. There was little effect of reduced frequency on the normal-force coefficient; however, increasing the reduced frequency produced an almost linear increase in the phase lag of the normal force. The moment coefficient was seen to increase with reduced frequency; however, the effects of reduced frequency on the moment phase angle were somewhat obscured because of a change in sign of the moment coefficient at zero frequency.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 4, 1953.

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Gage Location		
x/c Upper Surface		x/c Lower Surface
0.05		0.00
.10		.10
.20		.30
.30		.50
.40		.70
.50		.80
.60		.90
.68		.95
.72		
.80		
.90		
.95		

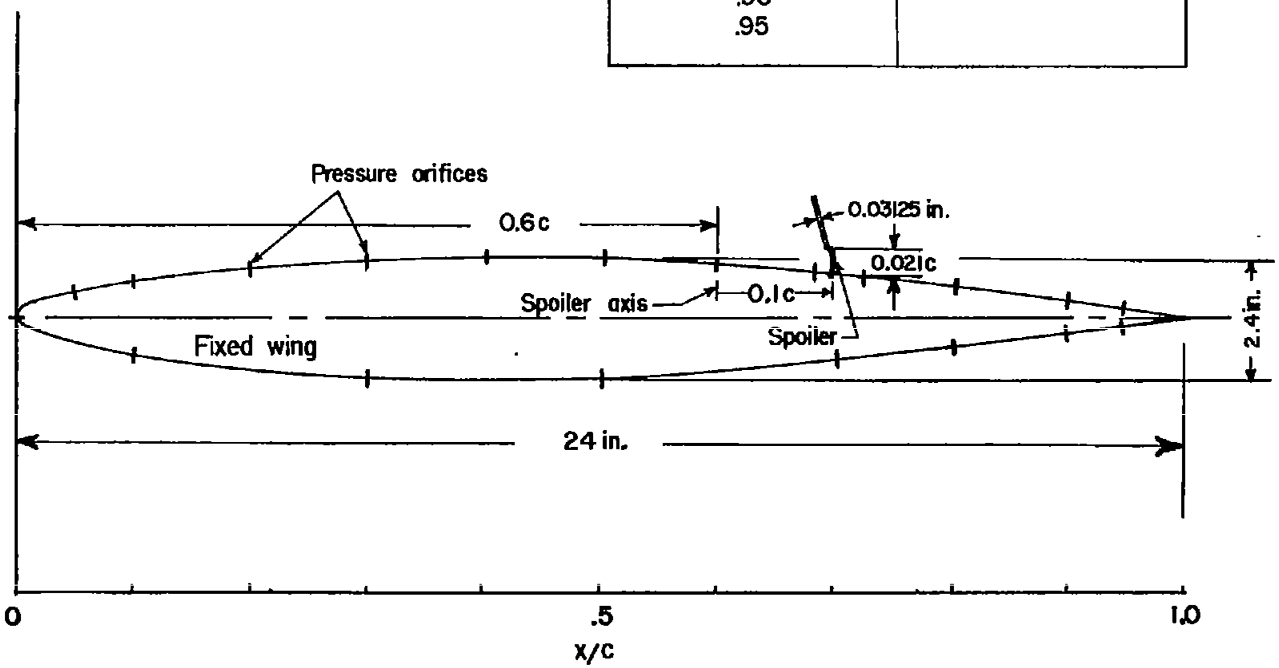

Figure 1.- Model geometry and location of pressure gages.

[redacted]

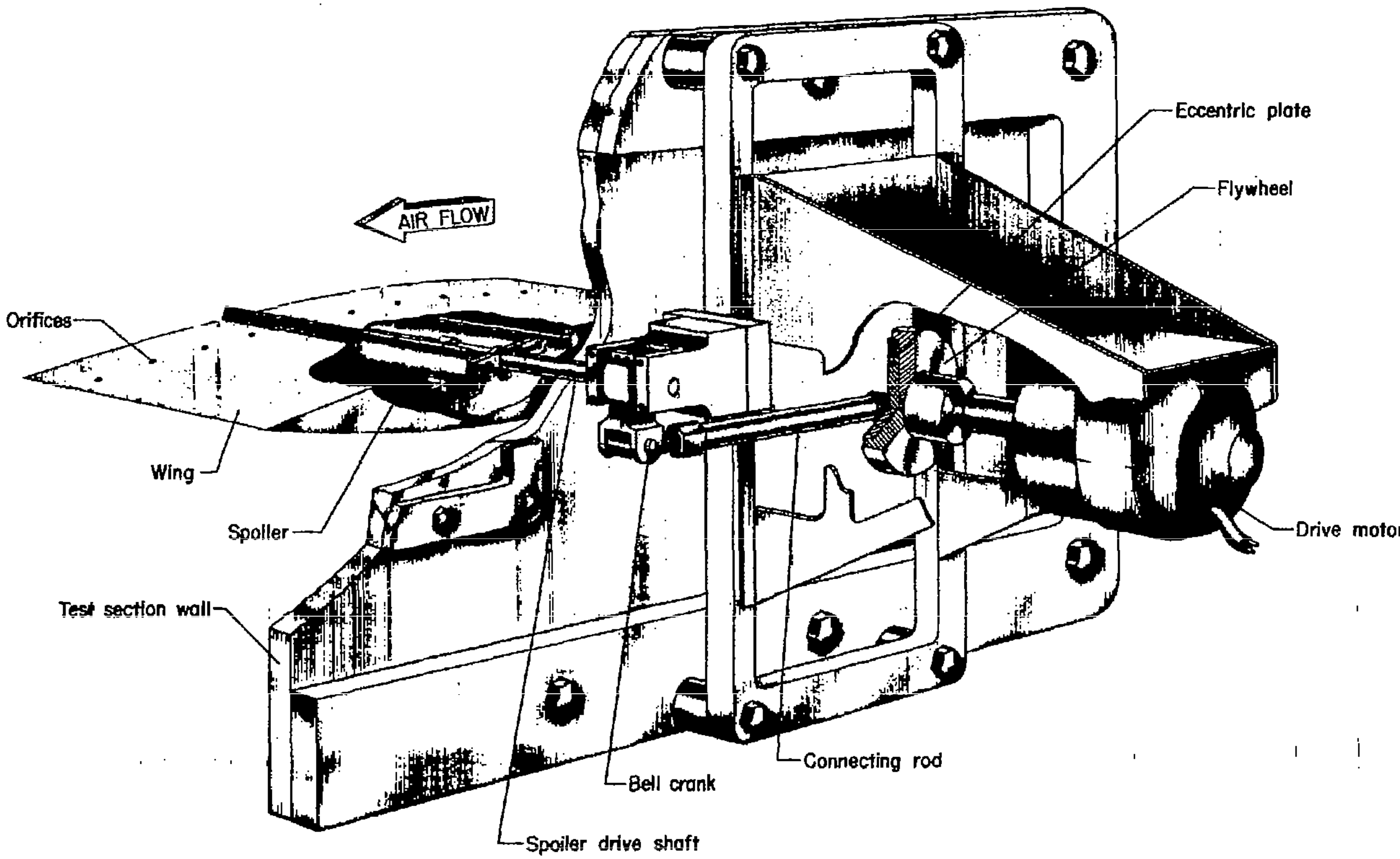

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Figure 2.- Schematic drawing showing motor-eccentric spoiler drive.

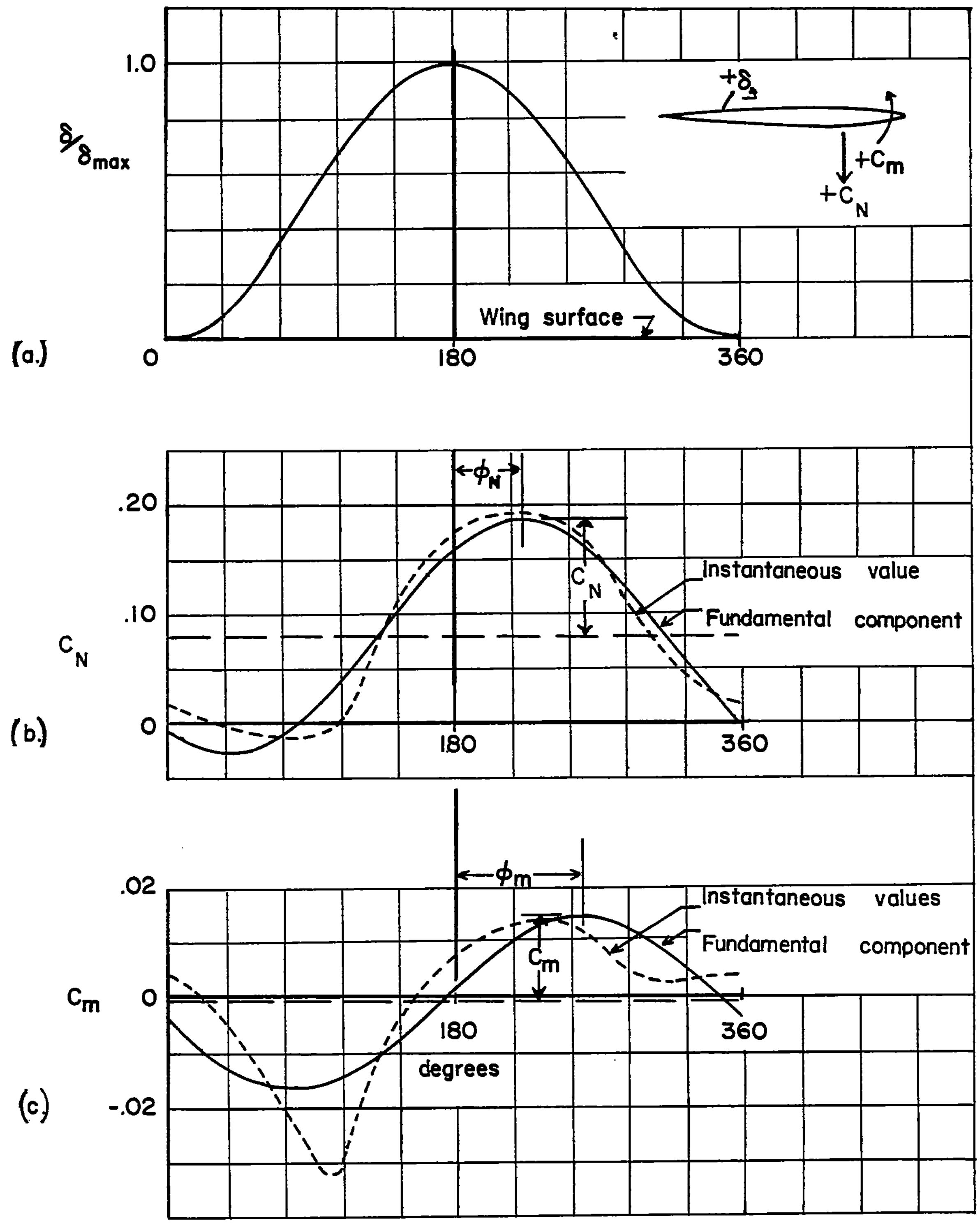


Figure 3.- Diagrams showing one cycle of oscillation of the spoiler and the corresponding force, moment, and phase angles.

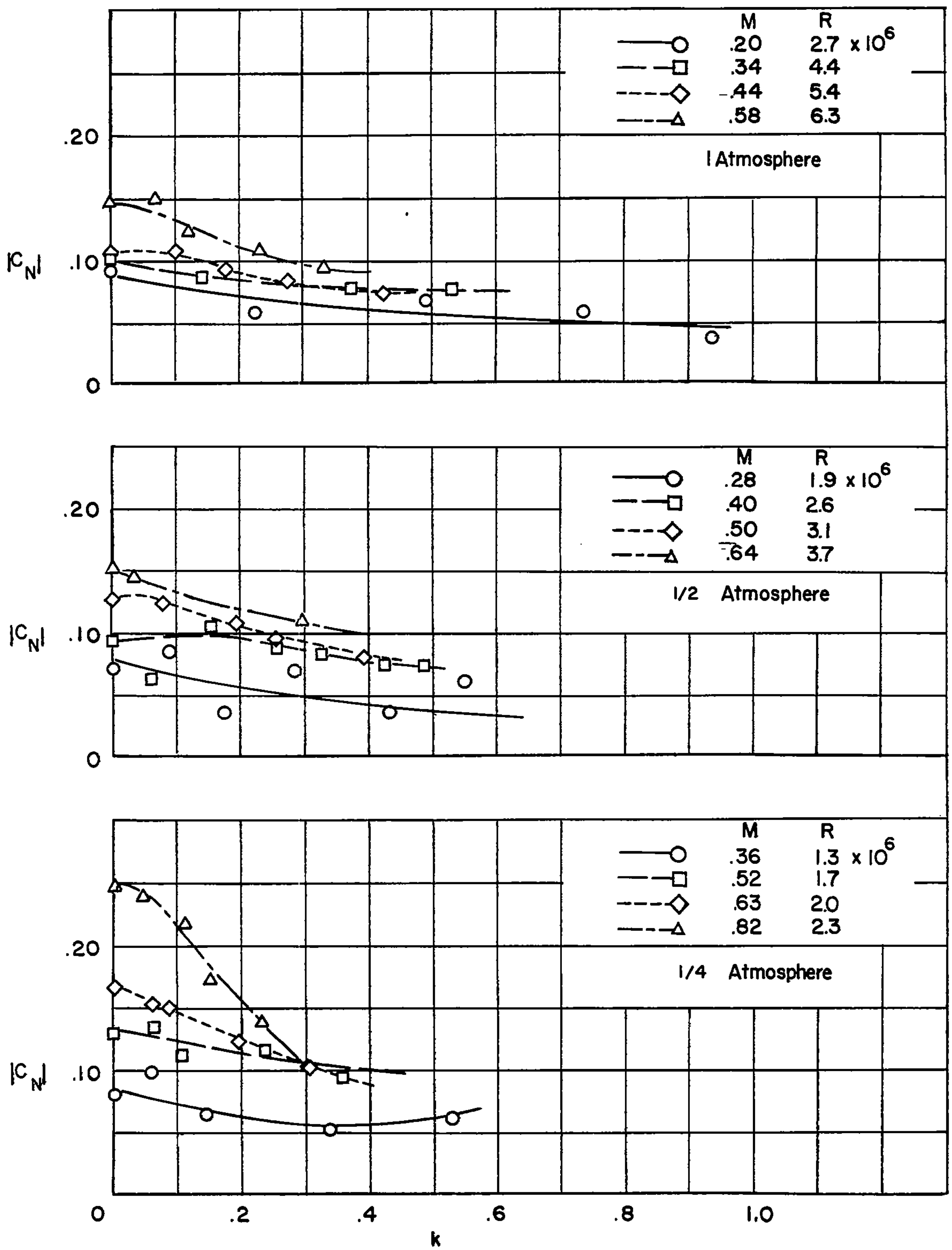


Figure 4.- Variation of $|C_N|$ with k.

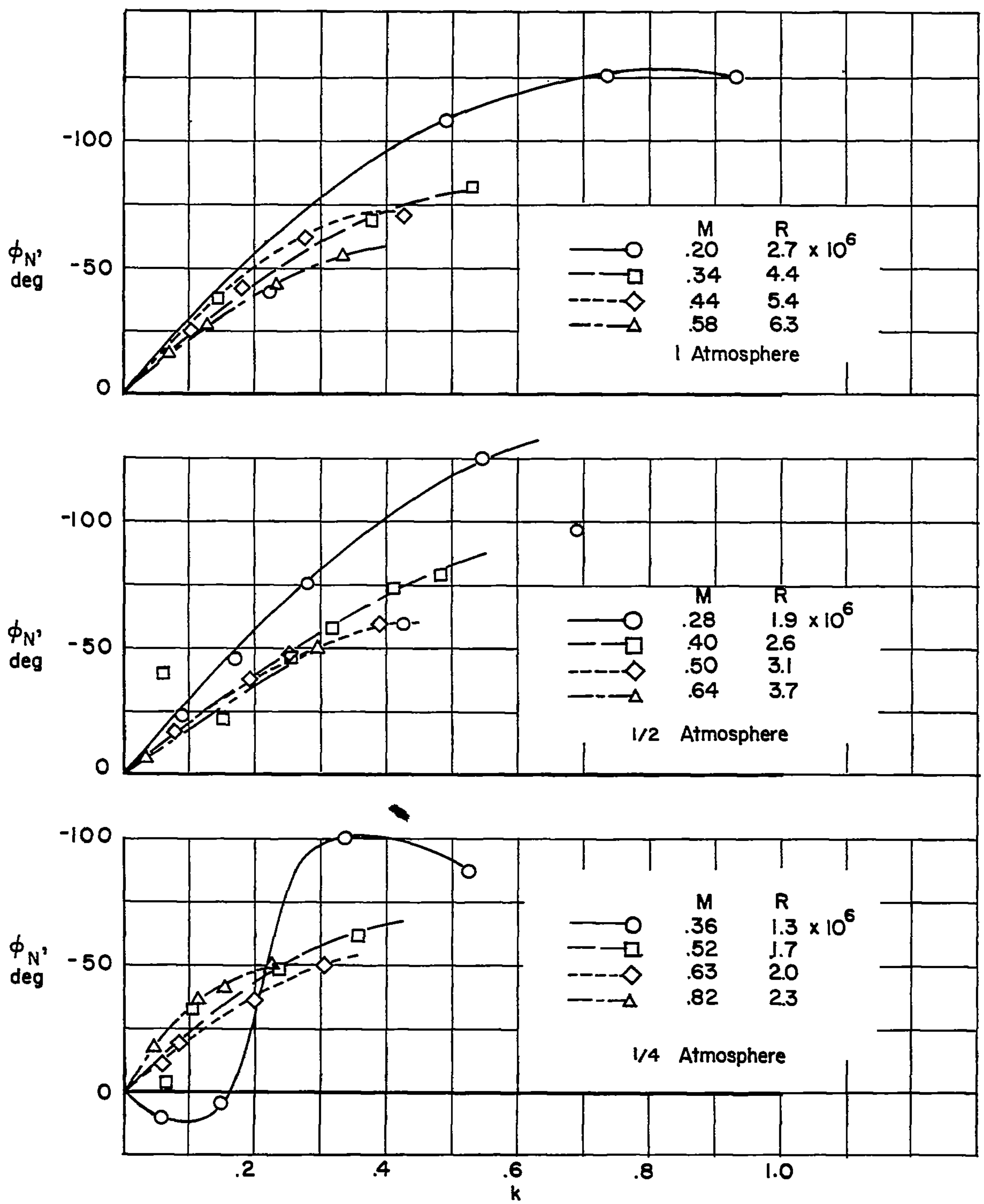


Figure 5.- Variation of normal force phase angle with k.

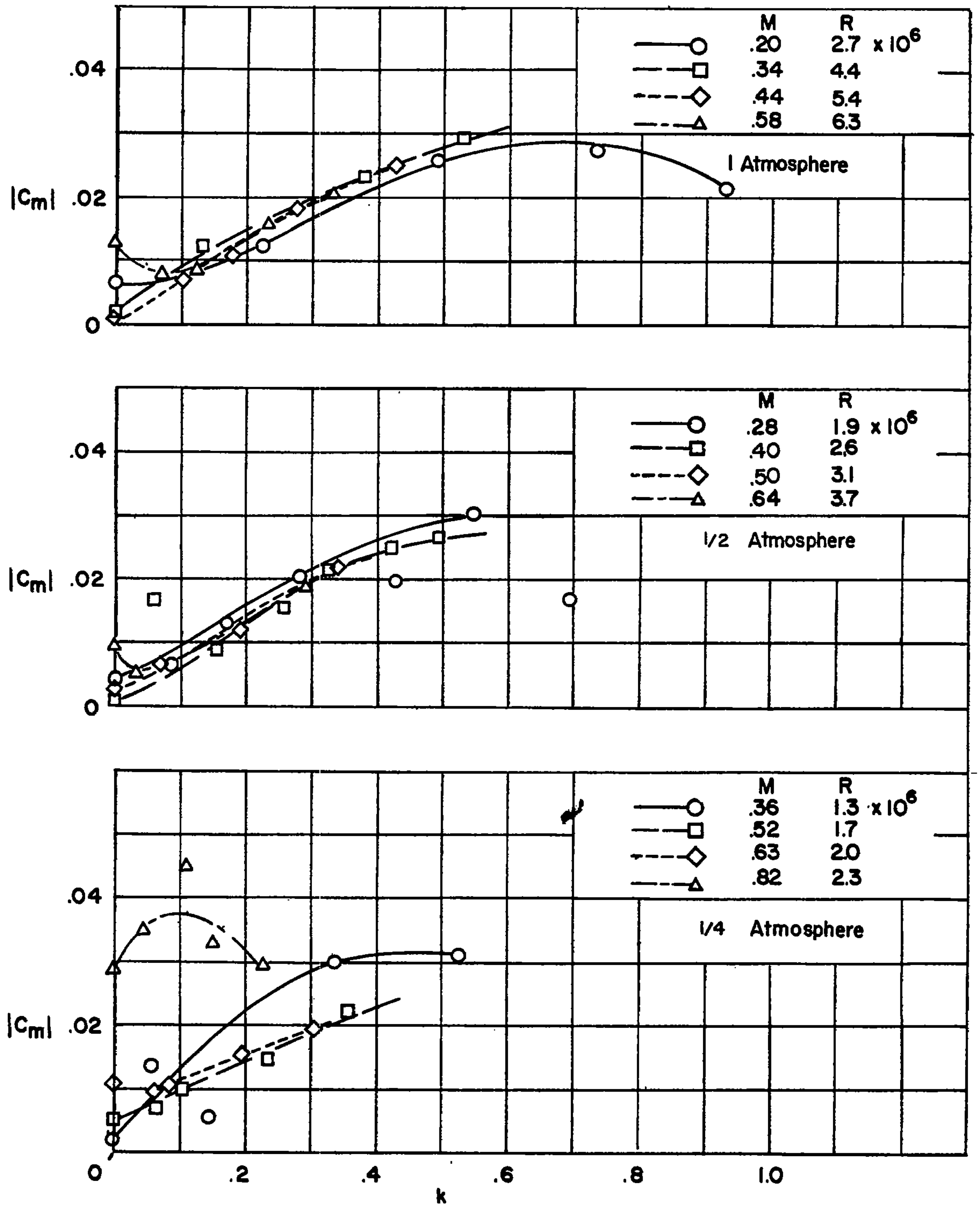


Figure 6.- Variation of $|C_m|$ with k.

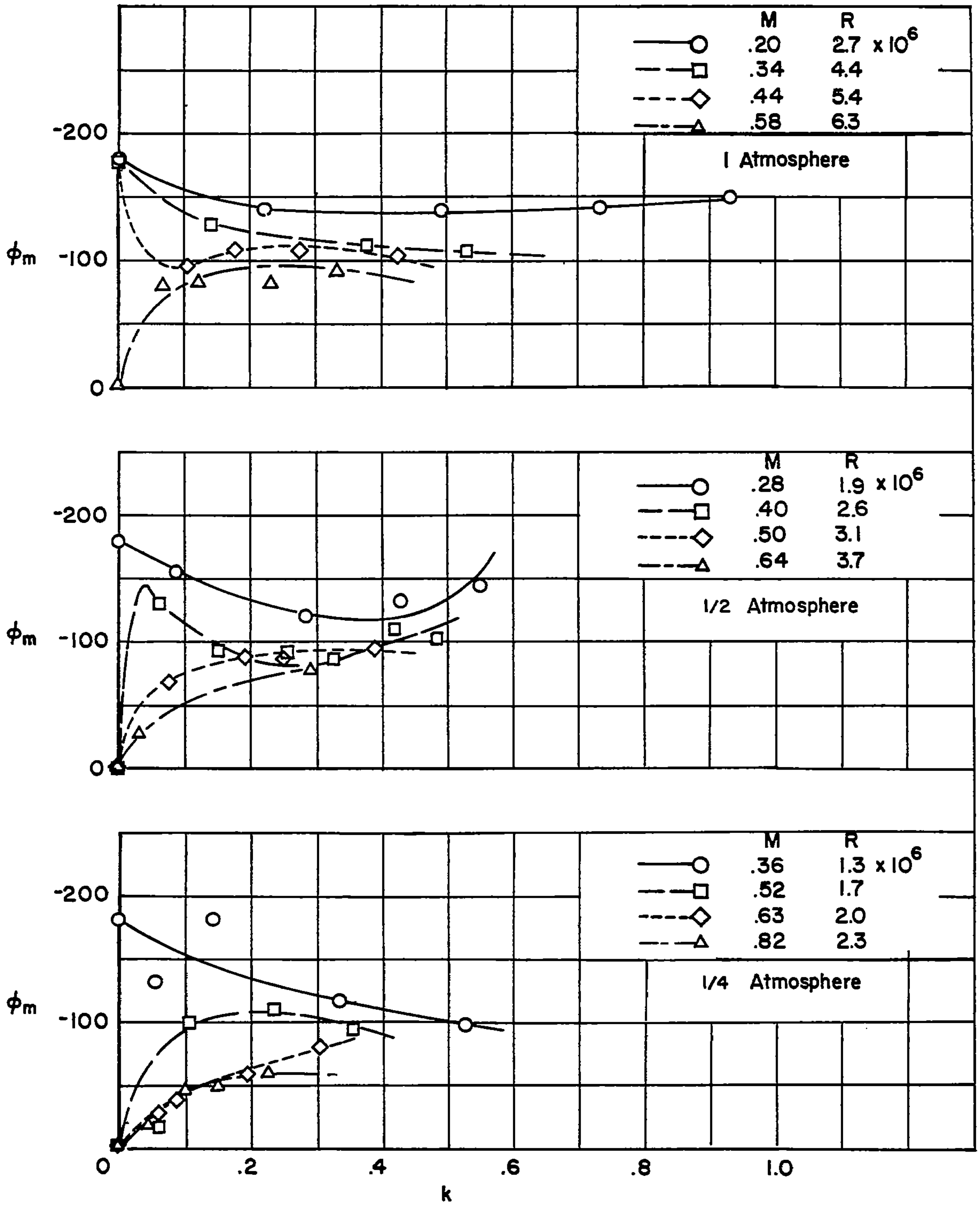


Figure 7.- Variation of ϕ_m with k.

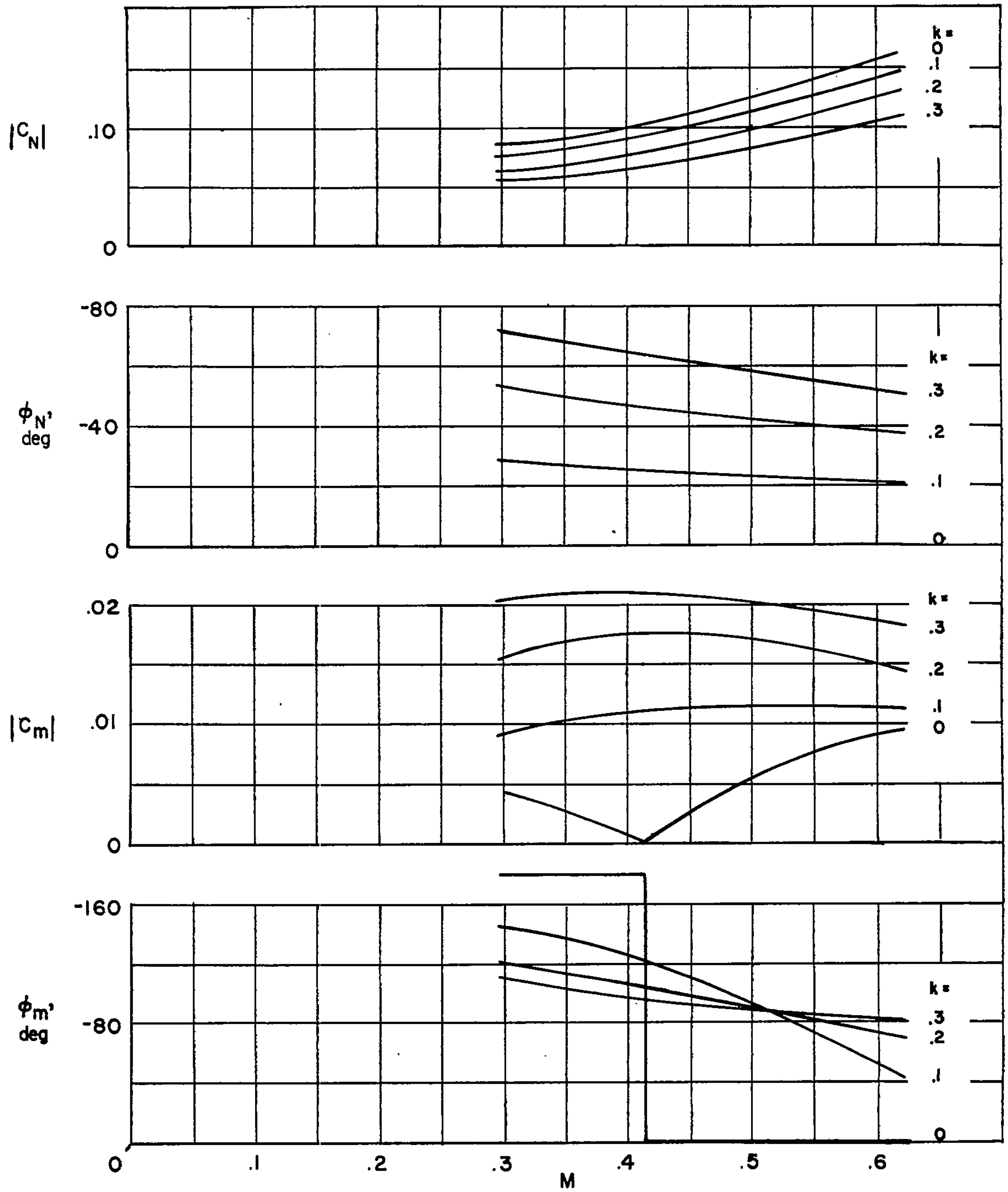


Figure 8.- Effect of M on $|C_N|$, ϕ_N, $|C_m|$, and ϕ_m. $R = 2 \times 10^6$.

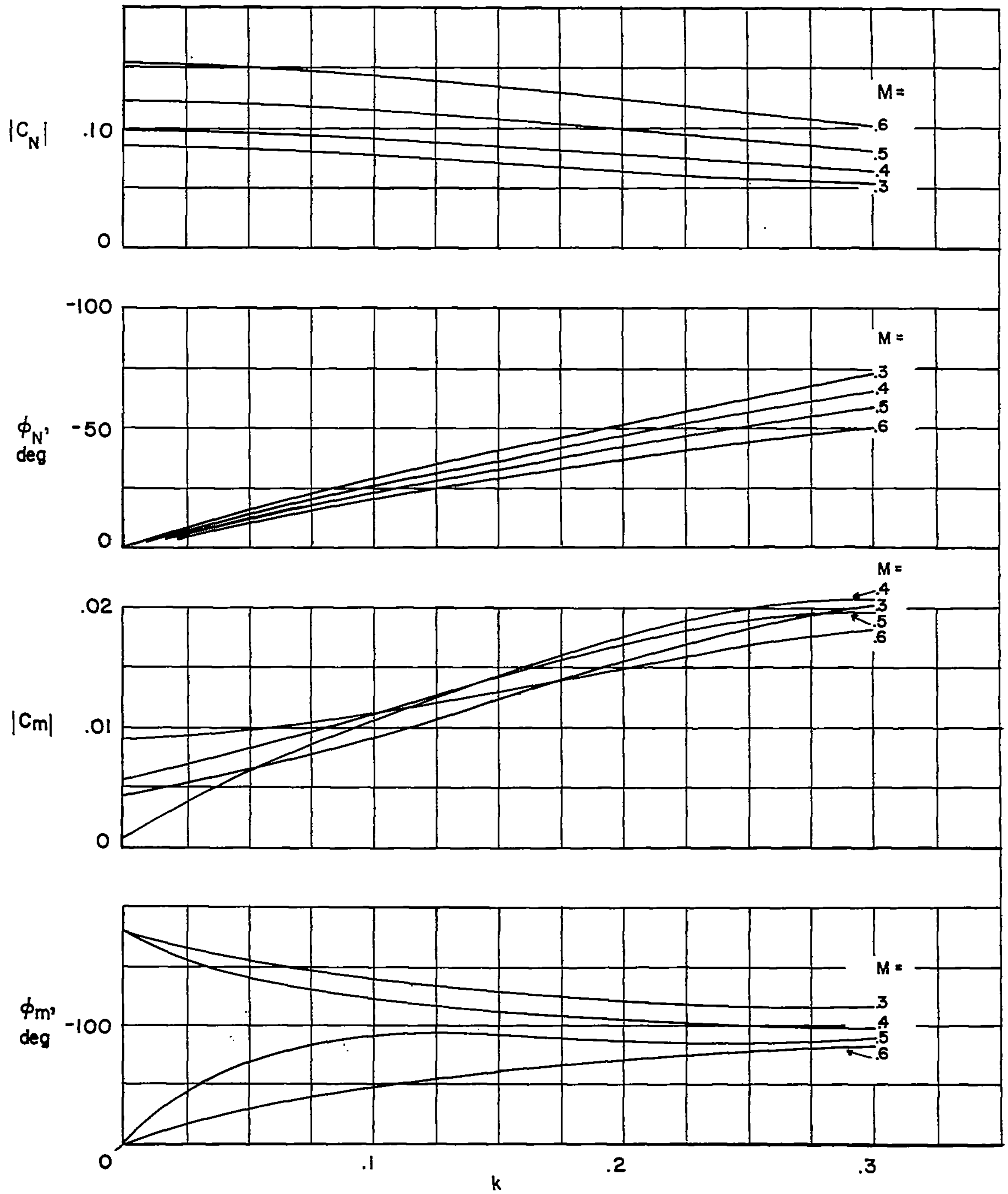


Figure 9.- Effect of k on $|C_N|$, ϕ_N, $|C_m|$, and ϕ_m. $R = 2 \times 10^6$.

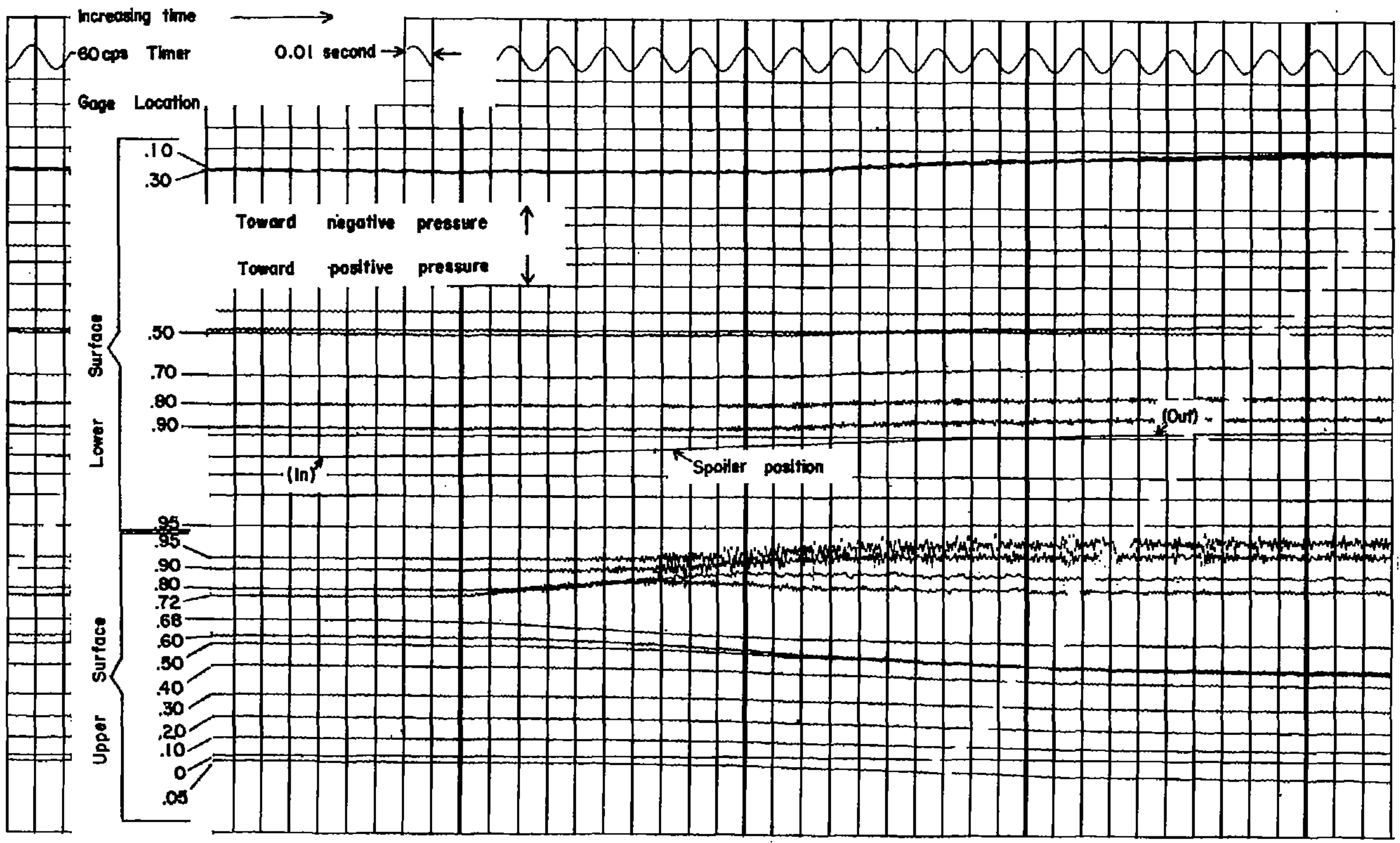


Figure 10.- Sample record of pressures and spoiler position as the spoiler slowly oscillates. $M = 0.58$; $R = 3.1 \times 10^6$; $k \approx 0$.

[redacted]

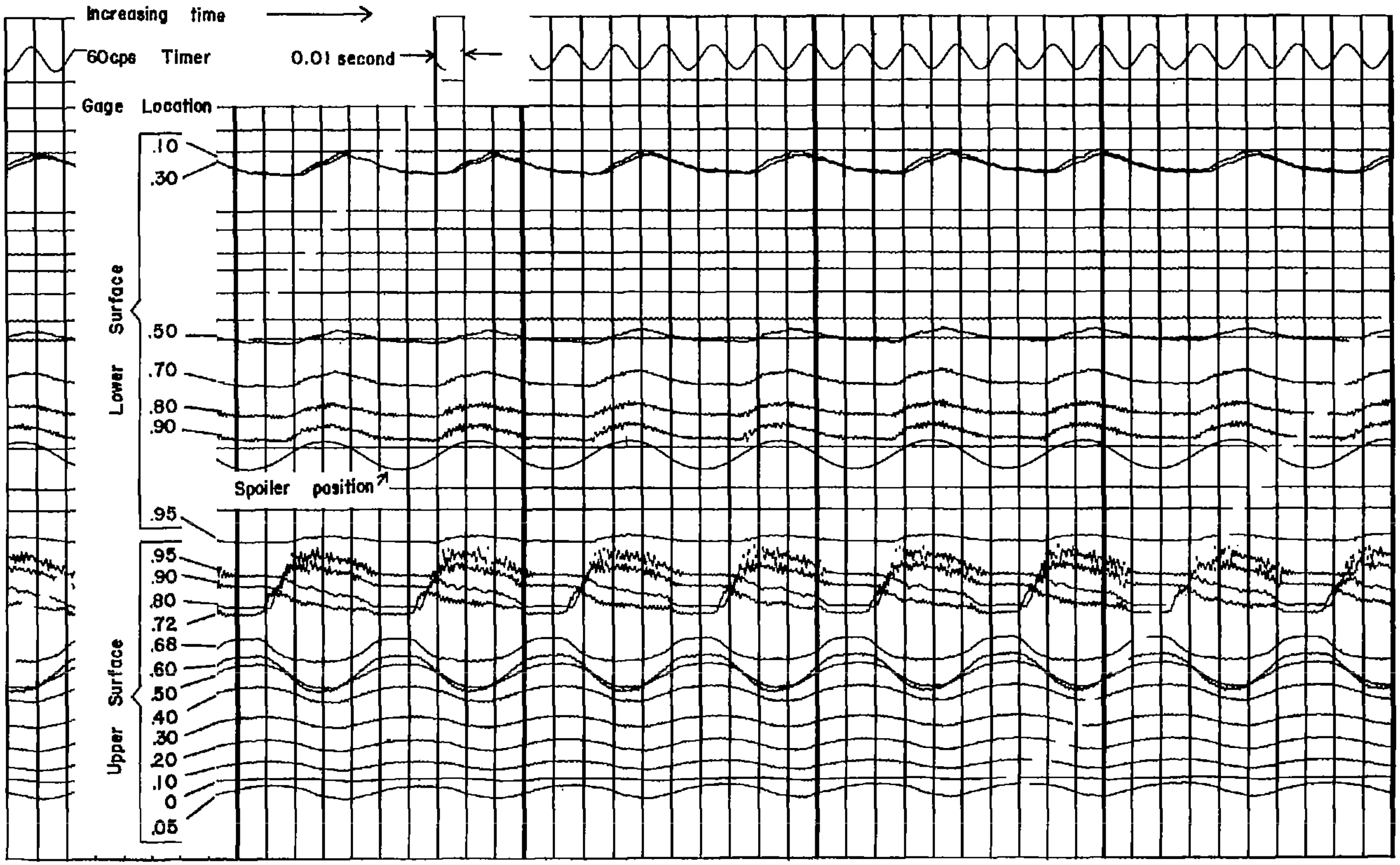
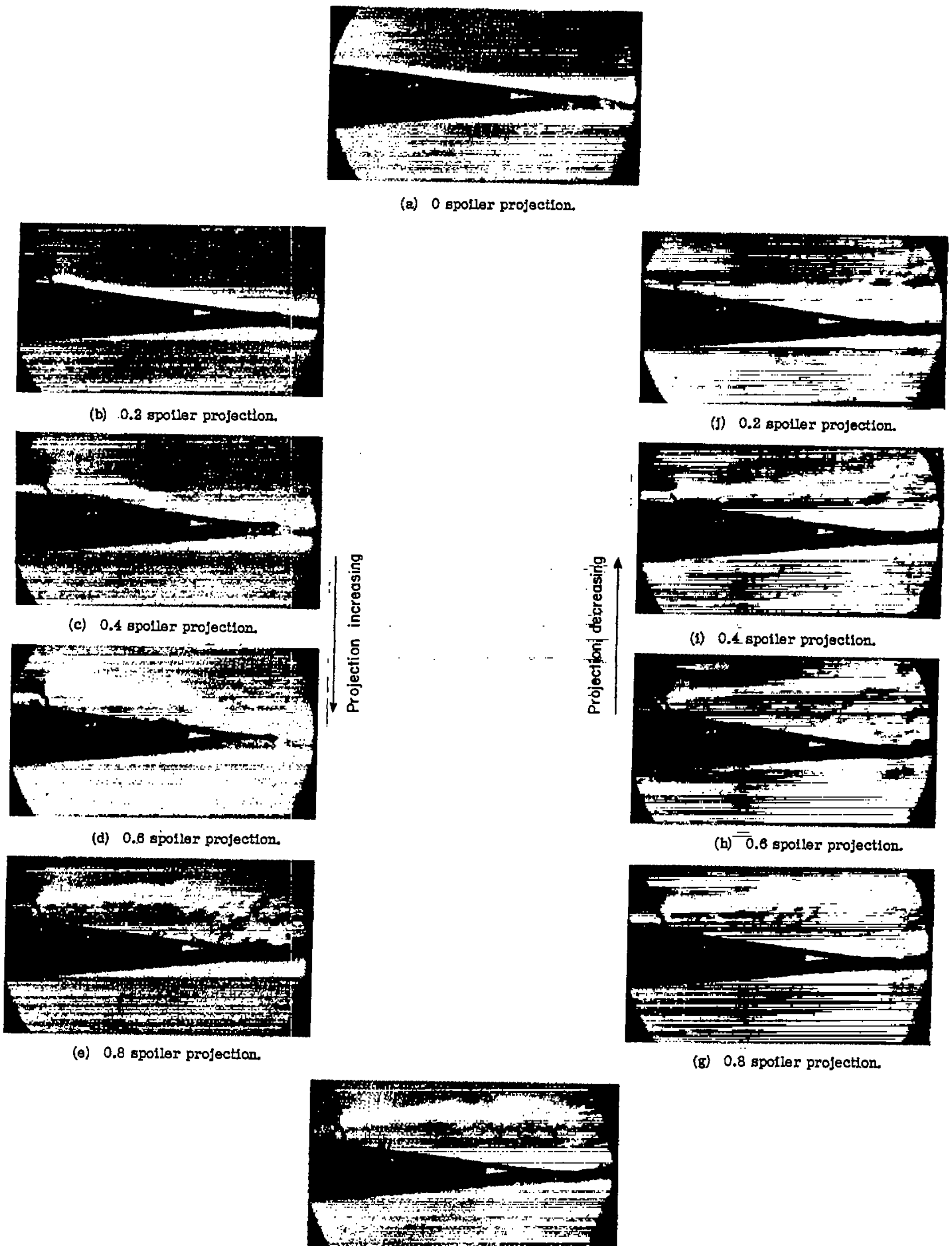


Figure 11.- Sample oscillograph record of pressures and spoiler position. $M = 0.58$; $R = 3.1 \times 10^6$; $k = 0.23$.

[redacted]



(a) 0 spoiler projection.

(b) 0.2 spoiler projection.

(c) 0.4 spoiler projection.

(d) 0.6 spoiler projection.

(e) 0.8 spoiler projection.

(f) Full spoiler projection.

(g) 0.8 spoiler projection.

(h) 0.6 spoiler projection.

(i) 0.4 spoiler projection.

(j) 0.2 spoiler projection.

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Figure 12.- Pictorial representation of the flow behind the spoiler at ten increments of one cycle. $M = 0.4$; $R = 5.26 \times 10^6$; $k = 0.27$.

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